Reconstruction of charged particles in the LHCb experiment

Bos, E.

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Summary

Particle physicists study the elementary particles and their interactions. The electromagnetic, weak and strong forces act between the various leptons and quarks, depending on their electric charge, weak isospin, and colour charge, by means of mediating gauge bosons. In the Standard Model, the electroweak interactions are treated by the GSW model and the strong force is described by QCD. In some weak decays, charge conjugation and parity are violated, as well as their combined operation. *CP* violation is one of the Sakharov conditions for a matter-antimatter imbalance, which is observed in the universe.

CP violation is embedded in the flavour structure of weak charged-current interactions. Those interactions convert up-type quark mass eigenstates into a superposition of down-type quark electroweak eigenstates, and vice versa, as prescribed by the CKM matrix. In the Wolfenstein parameterisation, this matrix is described by three rotation angles and one complex phase, the latter being the source of *CP* violation. Neutral B mesons can oscillate to and from their antiparticle state, which is referred to as mixing. This occurs in weak neutral interactions, where the mass eigenstates are linear combinations of the weak eigenstates. A difference between mass and weak eigenstates leads to a different transition probability from meson to anti-meson then from anti-meson to meson, being *CP* violation in mixing. *CP* violation in decay occurs when the decay amplitudes of *CP*-conjugate states are unequal. A third form of *CP* violation is found in the interference between mixing and decay amplitudes.

The LHC will offer proton-proton collisions for tests of the Standard Model and searches for additional physics at a centre-of-mass energy of 14 TeV and a design luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$. LHCb specialises in heavy-flavour physics, including the search for new physics in *CP* violation, and rare decays of beauty and charm hadrons. It is the intention of LHCb to make detailed measurements of $B_s^0 - \overline{B}_s^0$ mixing, using channels like $B_s^0 \to D_s^- \pi^+$, $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\eta$, in order to precisely determine the parameters ΔM_s, $\Delta\Gamma_s$ and ϕ_s. LHCb aims to improve the knowledge of the angle γ, while at the same time searching for signs of new physics. An approach of combining measurements of γ from tree-level only B decays, such as $B_s^0 \to D_s^{\mp} K^{\pm}$, $B^0 \to D^0 K^{*0}$ and $B^{\pm} \to D^0 K^{\pm}$, with those including box or penguin contributions, like $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$, is adopted. A difference between these measurements of γ may be due to new physics, present as virtual particles in the loop diagrams. From this perspective, the $B_s^0 \to D_s^{\mp} K^{\pm}$, $B_s^0 \to J/\psi\phi$ and $B_{(s)}^0 \to h^+h'^-$ decays are to be inspected.

The decay products of interest are predominantly present in two identical cones

around the beam-line, leading to a single-arm spectrometer design. LHCb has a silicon tracking detector or VELO to determine primary and secondary vertices. An integrated magnetic field of 4 Tm is used to bend charged particles, whose paths are further recorded by the TT, IT, and OT tracking sub-detectors. This allows for the momentum and charge of a particle to be determined. Particle identification and energy determination are facilitated by two RICH detectors, the electromagnetic and hadronic calorimeters and the muon system.

Both in the design of the detector and in the development of the software for the LHCb experiment, Monte Carlo simulation software is used. It offers a preview of what actual data can look like, and of the detector performance in various scenarios. This allows for fine tuning of reconstruction software and provides insight into the physics potential of LHCb.

The path of a charged particle through the LHCb detector is reconstructed from the hits that it causes in the position sensitive tracking sub-detectors. It is the purpose of the pattern recognition algorithms to determine which groups of hits belong to individual particles. The pattern recognition logic first determines the upstream or downstream starting points in the VELO or the T stations. These seeds are subsequently complemented by hits from the other tracking sub-detectors. In general, the pattern recognition algorithms aim to efficiently identify tracks, while examining as few combinations of hits as possible. To this end, they use cuts which have been tuned on Monte Carlo data.

Hits are fitted to a track model using a least-squares method, formulated as a Kalman filter. The track model is composed of extrapolation equations which account for the magnetic field, to which corrections for multiple scattering and energy loss are applied. The fit uses geometry information to identify the location of hits and material layers. Trajectories form an abstraction layer between the detector geometry description and the track reconstruction software. It eliminates the need to reformulate reconstruction equations upon a change in the geometry description. The Kalman filter is formulated with an averaging step in stead of a smoother step, making it more efficient and numerically stable. The fit procedure results in optimal estimates of the track parameters at discrete locations.

The track reconstruction produces in a final track sample of 85.2±0.05 tracks. Of these 25.4±0.05 are Long tracks, which are the main track type used for physics analyses. Long tracks contain on average 36.0±0.05 hits of the various tracking sub-detectors. The width of residual pull distributions of these hits is sensitive to misalignments and therefore offers an indication of detector alignment. Long track hit finding efficiency is 91.9±0.05% after outlier removal iterations, at a purity of 99.3±0.05%. At the reconstructed vertex, a Long track has a momentum resolution of 0.37±0.005% and a position resolution of 39.0±0.05μm. The coordinate and slope pulls are 10% too wide and the momentum pull is 25% too wide at the vertex, which leaves room for improvement. This issue is being addressed by improving on the estimation of hit errors and a study of the settings used in the treatment of material effects by Geant4.

Reconstructed tracks provide position, direction, momentum and charge information as input to physics analyses. The accuracy of the estimated slopes and momenta at a decay vertex influences the mass resolution of the mother particle. In case of $B_s^0 \to D_s^- \pi^+$ decays, the B_s^0 mass resolution of 17.45±0.27 MeV is dominated by the momentum resolution, whereas the 6.25±0.09 MeV mass resolution of the D_s^- is dominated by the slope resolution. Misidentifying a pion as a kaon in a $B_s^0 \to D_s^- \pi^+$ decay results in background for a $B_s^0 \to D_s^\mp K^\pm$ analysis. The track reconstruction offers a 2σ mass difference between the respective B_s^0 mass peaks for rejection of this background.

The proper-time resolution of the B_s^0 in $B_s^0 \to D_s^- \pi^+$ decays is 42.1±0.6 fs. A small proper-time resolution is important for measurements of the time-dependent *CP* asymmetry in the B_s^0 system. It dilutes the asymmetry measurement by a factor of 0.78±0.06 for $B_s^0 \to D_s^- \pi^+$ decays. Fitting the decay rate allows to identify the value of ΔM_s with an error of 0.008 ps, and the value of ω_{tag} to within 0.03.